MSFC-531

Conference Book Title
ASP Conference Series, Vol. XXX, YEAR
Editor 1, Editor 2 and Editor 3, eds.

New Evidence that CMEs are Self-Propelled Magnetic Bubbles

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Abstract.
We briefly describe the "standard model" for the production of coronal mass ejections (CMEs), and our view of how it works. We then summarize pertinent recent results that we have found from *SOHO* observations of CMEs and the flares at the sources of these magnetic explosions. These results support our interpretation of the standard model: a CME is basically a self-propelled magnetic bubble, a low-beta plasmoid, that (1) is built and unleashed by the tether-cutting reconnection that builds and heats the coronal flare arcade, (2) can explode from a flare site that is far from centered under the full-blown CME in the outer corona, and (3) drives itself out into the solar wind by pushing on the surrounding coronal magnetic field.

1. The Standard Model for CME Production

The scenario for CME production that is now often referred to as the "standard model" is presented in detail in Moore & Sterling (2006). This is the picture for ejective solar eruptions that was first put forth by Hirayama (1974) and has been modified and further supported by many subsequent observational and modeling studies (e.g., Kopp & Pneuman 1976; Heyvaerts et al 1977; Moore & LaBonte 1980; Sturrock et al 1984; Moore & Roumeliotis 1992; Shibata et al 1995; Rust & Kumar 1996; Moore et al 1997; Antiochos 1998; Shibata 1998; Antiochos et al 1999; Canfield et al 1999; Forbes 2000; Roussev et al 2003; Qiu et al 2004; Gibson et al 2004, 2006; Rust & LaBonte 2005; Wang 2006). In the present-day version of the standard model (e.g., Fig. 1 of Moore & Sterling 2006), the source of a CME, before it explodes, is a closed bipolar magnetic arcade, in which the core field, the field rooted near the polarity inversion line, is strongly sheared and twisted and is partly a sigmoidal flux rope. Dictated by specifics of the configuration and evolution of the field in and around the sheared-core arcade, eruption of the sigmoidal core field can be initiated via internal tether-cutting reconnection and/or external tether-cutting reconnection (breakout reconnection) and/or MHD instability. Whether or not internal tether-cutting reconnection is part of the eruption onset process, it is soon strongly driven between opposite-polarity stretched legs of the core field where they implode against each other below the erupting flux rope. This reconnection adds magnetic flux to the erupting flux rope above it and simultaneously adds an equal amount of flux to the growing flare arcade below it. The growing flux-rope "plasmoid with legs" explodes into

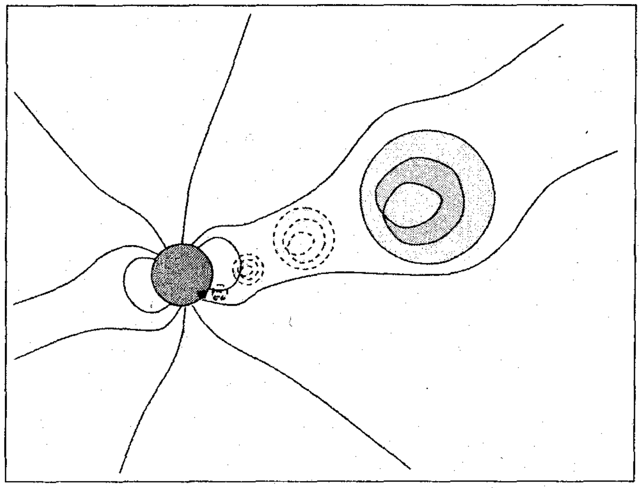

Figure 1. Schematic depiction of the stemming of the nearly radial magnetic field of the outer corona from non-radial fields of the inner corona, and the consequent over-and-out progression of a CME that explodes from a suitably located source region.

the outer corona as the interior of the CME. The whole CME explosion is driven by the magnetic pressure of its flux-rope-plasmoid interior, which is built and unleashed by the tether-cutting reconnection, and which drives the CME out into the solar wind by pushing against the ambient coronal magnetic field.

Evidence that CMEs are driven by their magnetic pressure was pointed out before *Yohkoh* (Moore 1998a,b). As was anticipated (Moore 1991), *Yohkoh* X-ray movies of sigmoid eruptions verified that sheared-core arcades erupt according to the standard model (Sterling et al 2000; Moore et al 2001). We have found new evidence from *SOHO* that CMEs are driven by their magnetic pressure (Moore et al 2007).

2. New Observations Explained by the Standard Model

Our recent studies of CME explosions observed by *SOHO* indicate that whether an explosion of a sheared-core arcade produces a CME, and if it does, whether the CME explodes nearly radially outward from its source or instead is an "over-and-out" CME like that sketched in Figure 1, depend as much on the strength and arrangement of the largr-scale magnetic field in which the exploding arcade is embedded as on the size and field strength of the exploding arcade.

In Bemporad et al (2005), we reported a particular variety of over-and-out CME that we call "streamer puffs." From the observations, we inferred that a streamer-puff CME is driven by the magnetic pressure of a flux-rope plasmoid that explodes from a compact sheared-core arcade embedded in one foot of an outer loop of the large magnetic arcade that forms the base of a coronal streamer. The exploding plasmoid is guided up the leg of the large loop by the field of the streamer arcade, but has enough magnetic pressure to blow out the top of the

loop, thereby producing a streamer-puff CME that travels out along the radial path of the streamer. Moore et al (2007) reported a streamer-puff CME that was driven by an exceptionally strong explosion of a compact sheared-core arcade in a foot of the blown-out loop of the streamer arcade. In this event, strong coronal dimming occurred in the remote non-flare foot of the blown-out loop, confirming the Bemporad et al (2005) magnetic-arch-blowout scenario for the production of streamer-puff over-and-out CMEs. This scenario is a version of the standard model (see Moore et al 2007).

The observed production of streamer-puff CMEs suggested to us that when any CME-producing flux-rope plasmoid explodes from a sheared-core arcade, its pressure, which is nearly all magnetic, exceeds the surrounding coronal pressure, which is also mostly magnetic. In Moore et al (2007) we therefore surmised that as the flux-rope plasmoid erupts out through the corona it expands laterally until it achieves lateral pressure balance with the surrounding corona. The lateral pressure balance of the CME with the coronal field beyond 2—3 R_{Sun}, which is nearly radial (as in Fig. 1), results in the CME attaining a final constant heliocentric angular width, Θ_{CME}, in the outer corona. This, and the implication of the standard model that the magnetic flux content of the full-blown CME is roughly the same as that in the full-grown flare arcade produced by the same reconnection that builds the CME plasmoid, yield the following simple approximate equation that can be tested by measuring Θ_{CME} of an observed CME in the outer corona and measuring the heliocentric angular width Θ_{Flare} of the full-grown co-produced flare arcade: $B_{Flare} \approx 1.4(\Theta_{CME}/\Theta_{Flare})^2$ G, where B_{Flare} is the flare-site field strength required if the standard model is essentially the right physical picture for CME production. The coefficient 1.4 in this equation is set by the strength of the radial magnetic field in the outer corona, which we estimated by extrapolation from the radial component of the interplanetary magnetic field measured by *Ulysses*.

Table 1: Test Results

CME (date)	Source Region	Θ_{CME} (deg)	Θ_{Flare} (deg)	Rqrd B^*_{Flare} (Gauss)	Rqrd B_{Flare} Fits Source Region? (Yes/No)	Source Region Mag. Energy** (ergs)
2002 May 20	Centered on small δ spot	41	2.2	**$\approx$ 490**	**Yes**	**$\sim 10^{32}$**
1999 Feb 9	QR filament arcade	64	27	**$\approx$ 8**	**Yes**	**$\sim 10^{32}$**
2003 Nov 4	Centered on giant δ spot	128	8.7	**$\approx$ 300**	**Yes**	**$\sim 10^{33}$**

* Required $B_{Flare} \approx 1.4(\Theta_{CME}/\Theta_{Flare})^2$ Gauss
** Source Region Magnetic Energy $\equiv (B^2/8\pi)(\Theta_{Flare}R_{Sun})^3$

In Moore et al (2007), we tested this equation against three well-observed CMEs that exploded from radically different source regions. For each event, the

equation gave a value of B_{Flare} that was appropriate for the magnetic setting of the source of the CME explosion, and was strong enough for the pre-eruption sheared-core arcade to have had ample free magnetic energy to have produced the explosion (see Table 1). This positive test indicates that the standard model is essentially the correct picture for CME explosions, and that a CME is basically a magnetic bubble that drives itself out into the solar wind by pushing on the surrounding coronal magnetic field (Moore & Sterling 2006; Moore et al 2007).

Acknowledgments. This work was funded by the Heliophysics Division of NASA's Science Mission Directorate.

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